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ABSTRACT

In this study, multidimensional scaling (MDS) was used to measure how 23 chemical engineering seniors categorized key design terms at the beginning and end of a capstone design course. An on-line method was developed to collect the MDS data. The results suggest that some important design concepts were not well understood, even at the end of the semester. Results of the MDS cluster analysis were used to help indicate where students had accurate knowledge of engineering design and where their knowledge was incomplete. The instructional implications of these results are discussed. (Contains 3 figures and 12 references.) (SLD)

Using an on-line tool to investigate chemical engineering seniors' concept of the design process

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Abstract

Engineers must understand how to design products and processes, and therefore design courses are often the culminating experience in an engineering student's undergraduate education. How well do graduating seniors understand the concept of "design?" In this study, multidimensional scaling (MDS) was used to measure how chemical engineering seniors categorized key design terms at the beginning and end of a capstone design course. An on-line method was developed to collect the MDS data. The results suggest that some important design concepts were not well understood, even at the end of the semester. The instructional implications of these results are discussed.

Introduction

The design process is a cornerstone of engineering and is a common subject of engineering education research (Atman & Bursic, 1998; Wankat, 1999). Since practicing engineers must understand how to design products and processes, engineering students often are required to complete a "design" course in their senior year. These courses are often called "capstone" courses, because they are seen as the culminating experience in an engineering student's undergraduate education.

How do students on the threshold of entering the chemical engineering profession view this key concept? In this study we have investigated how chemical engineering seniors in a capstone design course view the concept of "design." We also discuss how our results may provide feedback to engineering educators to improve instruction.

In this study, we use multidimensional scaling (MDS) to measure cognitive structure (or the underlying configuration of a person's knowledge). Multidimensional scaling (Kruskal & Wish, 1978) is the name for a family of methods that convert similarity judgments into physical distance. The use of MDS for representing cognitive structure has been validated by Champagne, Hoz & Klopfer (1984) and Shavelson (1985) and has been used in this way by Markham, Mintzes, & Jones (1994) and Streveler (1994).

The first step in MDS analysis is to ask participants to group together terms that they believe to be conceptually linked. This information is averaged and converted to a

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similarity matrix that is then input into the MDS procedure for analysis. MDS analysis then finds a model (in 2 to n dimensions) that is the best fit of the similarity matrix.

In the MDS results, items seen as similar to one another will be plotted closely together. One can look at the MDS output, see which items students view as belonging together, and gain insight into how students are organizing the information they are learning. If the MDS analysis reveals terms clustered together "incorrectly" this may signify a potential misconception. A "misplaced" term, in other words one that is placed with other terms in an unexpected way, may be an indicator of a misconception about that term (Streveler & Bail, 1992; Streveler & Miller, 1999).

We suggest that using MDS to help locate areas of student misunderstanding may be seen as a useful classroom assessment technique. The purpose of classroom assessment techniques is to give instructors informal feedback about what their students are learning (Angelo & Cross, 1993; Cross & Steadman, 1996) and the results of classroom assessment techniques are best used to improve learning (Cross, 1998). As will be seen in this paper, the MDS results served this purpose in this study. We also created an on-line method for gathering MDS data from students that has the potential to make this rather esoteric form of analysis more accessible to classroom instructors.

Methods

Participants in our study were 23 chemical engineering seniors enrolled in a capstone senior design course at the Colorado School of Mines. As stated above, we used MDS to measure the students' cognitive structure. The following steps were used to conduct this study.

1) The course professor selected terms that were deemed to be central to understanding chemical engineering design. The 32 terms selected by the instructor for the clustering task are listed in Table 1.

2) In order to increase the ease of use, a method of gathering the clustering data on-line was developed and used in this study. As shown in Figure 1, a web page was created which listed the 32 terms in alphabetical order. Radio buttons allowed students to cluster the terms into one of nine possible groups. A PERL database was created to collect the data. The database collected the name of the student, their id number, the date the clustering task was completed, and the group number of each of the 32 terms.

3) At the beginning of the semester, students were given the extra credit assignment of going to the class web page, and clustering the 32 terms into logical groups. A total of 22 students completed the pretest (96% of students registered for the design course).

Table 1. Design terms, selected by the instructor and used by students in the clustering task.

Term number	Term name
Term 1	capital cost
Term 2	cash flow analysis
Term 3	conceptual design
Term 4	debottlenecking
Term 5	design heuristic
Term 6	economic optimum
Term 7	energy transfer block
Term 8	engineering design process
Term 9	engineering judgment
Term 10	equipment heuristic
Term 11	generic block flow diagram
Term 12	HAZOP analysis
Term 13	input-output diagram
Term 14	life-cycle analysis
Term 15	maintenance cost
Term 16	operating cost
Term 17	operating heuristic
Term 18	piping and instrumentation diagram
Term 19	process analysis
Term 20	process bottleneck
Term 21	process evaluation
Term 22	process flow diagram
Term 23	process optimization
Term 24	process simulation
Term 25	process synthesis
Term 26	rate of return
Term 27	reaction block
Term 28	risk analysis
Term 29	separation block
Term 30	technical optimum
Term 31	time value of money
Term 32	troubleshooting

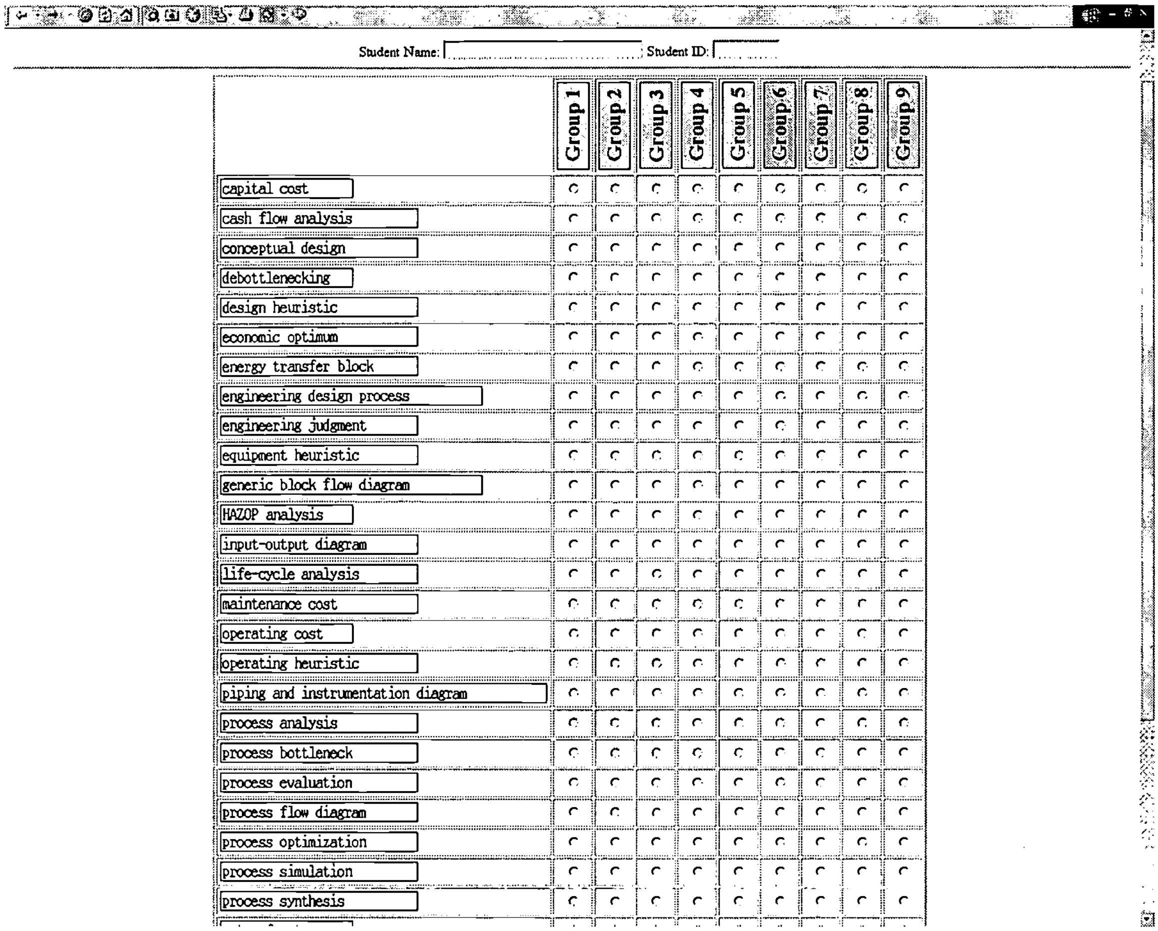

Figure 1. Screen Capture of the MDS Webpage

4) The assignment outlined in step 3 was repeated during the last week of instruction. A total of 14 students completed the posttest (61% of the students in the course).

5) The database described in step 2 was emailed to the investigators after the students had completed the pretest, and again after the posttest was completed.

6) These data were then input into the statistical package, SAS, and a similarity matrix was computed. This matrix was then used as the input to compute the MDS solution.

Results

The model representing the MDS solution may be expressed in 2 to n dimensions. A statistic called "stress" gives us a goodness-of-fit measure. The "Stress" measure for a two-dimensional solution was below 1.5 on both the pretest and posttest. This result showed that a 2-dimesional solution was adequate in both cases.

The two-dimensional solutions for the pretest (Figure 2) and posttest (Figure 3) are shown below. It is customary to name the axis dimensions expressed in a MDS solution (much as one names factors in factor analysis). Based on the clustering results obtained, we labeled the x-axis "economic vs. technical" and the y-axis "process vs. product." (Refer to Table 1 for the listing of term numbers and term names.) The solution of the pretest was rotated for more consistent placement of pretest and posttest clusters in the same quadrants, thus allowing for easier pretest-posttest comparisons.

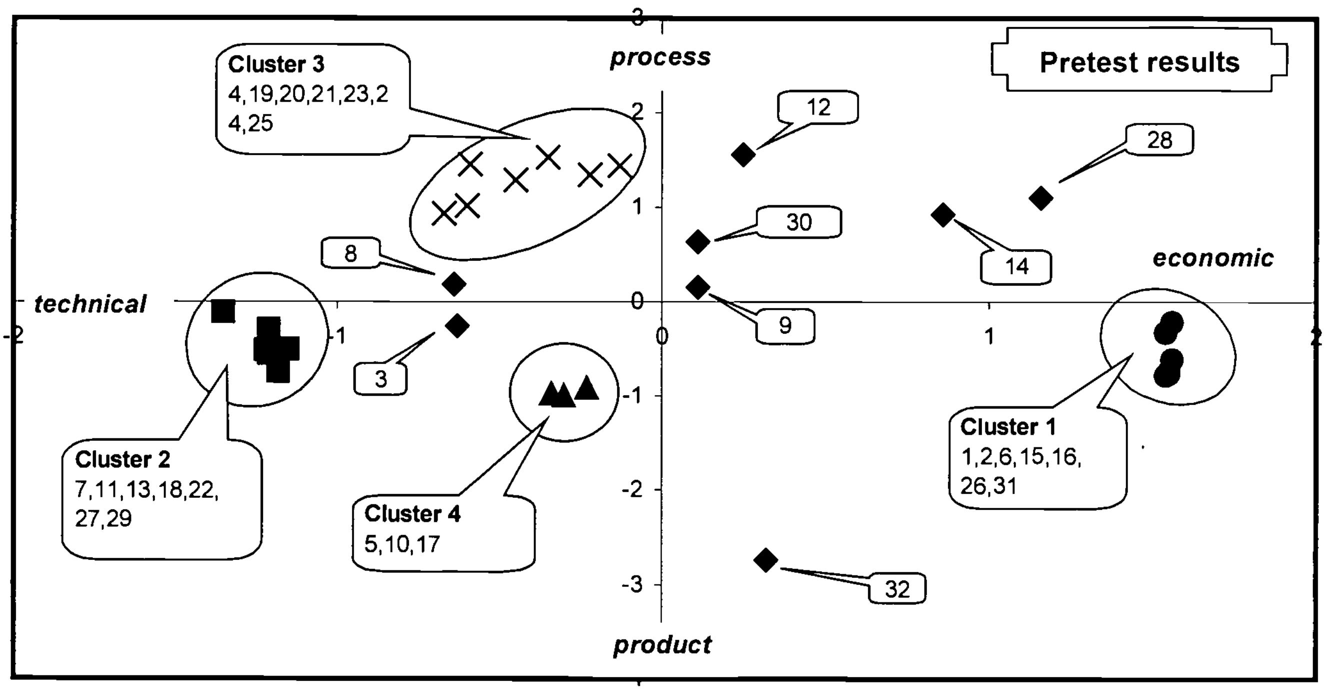

Figure 2. Pretest Results of MDS Analysis for Senior Design Terms

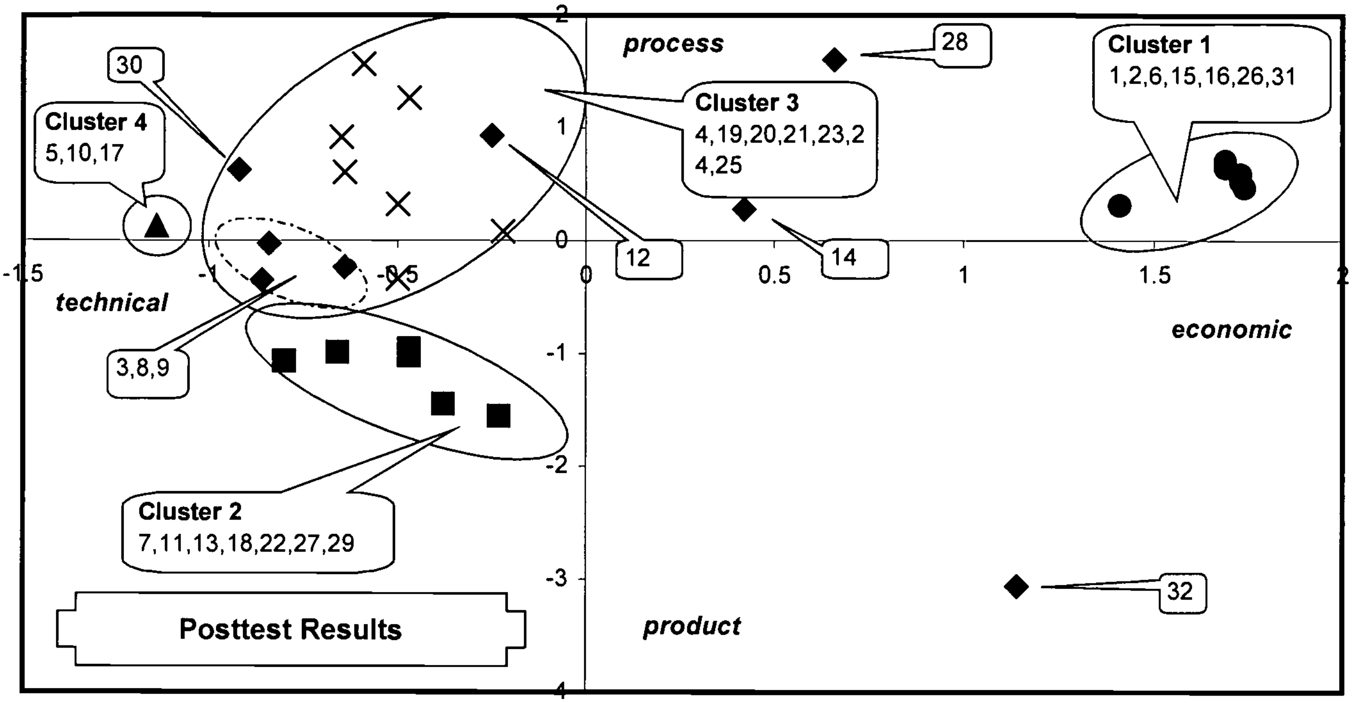

Figure 3. Posttest Results of MDS Analysis for Senior Design Terms

In the pretest (Figure 2) four distinct clusters of terms were observed:

1- A cluster containing all terms that pertained to the economic analysis of a project: capital cost (Term 1), cash flow analysis (Term 2), economic optimum (Term 6), maintenance cost (Term 15), operating cost (Term 16), rate of return (Term 26), time value of money (Term 31). We will call this grouping Cluster 1. These terms are shown as circles in Figures 2 and 3.

2- A cluster listing process flow diagram terms: energy transfer block (Term 7), generic block flow diagram (Term 11), input-output diagram (Term 13), piping and instrumentation diagram (Term 18), process flow diagram (Term 22), reaction block (Term 27), separation block (Term 29). We will call this grouping Cluster 2. These terms are shown as squares in Figures 2 and 3.

3- A cluster containing terms that described analysis of processes: debottlenecking (Term 4), process analysis (Term 19), process bottleneck (Term 20), process evaluation (Term 21), process optimization (Term 23), process simulation (Term 24), process synthesis (Term 25). We will call this grouping Cluster 3. These terms are shown as X's in Figures 2 and 3.

4- And a cluster with three terms containing the word heuristic: design heuristic (Term 5), equipment heuristic (Term 10), operating heuristic (Term17). We will call this grouping Cluster 4. These terms are shown as triangles in Figures 2 and 3.

Other terms were scattered around the plot and could not easily be placed into clusters in the pretest. These terms are: conceptual design (Term 3), engineering design process (Term 8), engineering judgment (Term 9), HAZOP analysis (Term 12), life-cycle analysis (Term 14), risk analysis (Term 28), technical optimum (Term 30) and troubleshooting (Term 32). These terms are shown as diamonds in Figures 2 and 3.

How does the position of these terms change in the posttest? As shown in Figure 3, Clusters 1, 2, 3, and 4 all remain in the posttest. However, some of terms are added to Cluster 3 (analysis of processes) in the posttest. The terms conceptual design (Term 3), engineering design process (Term 8), and engineering judgment (Terms 9), HAZOP analysis (Term 12) and technical optimum (Term 30) all become part of Cluster 3.

The three heuristic terms (Terms 5, 10, and 17) in Cluster 4, become so closely clustered in the posttest that they merge into a single point. However, these three points also become more closely associated with Cluster 3.

Three terms: life-cycle analysis (Term 14), risk analysis (Term 28), and troubleshooting (Term 32) continued to not be closely associated with any cluster of terms in the posttest.

Discussion

The design instructor determined that Clusters 1 and 2 were clustered accurately in both the pretest and posttest and we can infer that students have adequate understanding of the terms in these areas. Students included all terms dealing with economic analysis in Cluster 1 and indeed students in this capstone design course have previously completed an engineering economics course and did have a strong background in economics. Students also are familiar with design terms and this is shown in the clustering of terms in Cluster 2.

In the pretest, Cluster 3 contained many terms which include the word "process;" however inclusion of the word "debottlenecking" in this cluster suggests that students used deeper characteristics to cluster these terms.

In the posttest, five terms were added to Cluster 3. The terms conceptual design (Term 3), engineering design process (Term 8), and engineering judgment (Terms 9) now become part of Cluster 3 suggesting that students learned the importance of conceptualizing processes using engineering judgment when designing and analyzing chemical processes. The terms HAZOP analysis (Term 12) and technical optimum (Term 30) also became part of Cluster 3 in the posttest, which may indicate that students in the course learned about the importance of analyzing a process for the potential of hazardous operations

(HAZOP) and the importance of determining how to optimize the technical operation of a process (in addition to economic optimization).

All the words in Cluster 4 include the word "heuristic" even though the three terms are not related in a deeper, more fundamental way. It is likely that this is an example of the use of surface characteristics to group terms. We note that Cluster 4 remains intact in the posttest and in fact clusters even closer (the three terms are plotted as the exact same point). Thus the use of surface characteristics to cluster these terms seems to become stronger at the end of the semester even though the course included several lengthy discussions about the utility of heuristics to perform rapid design calculations and check detailed computer simulation results. This may indicate that even at the end of the course, students do not have a deep understanding of these terms. However, since these terms move closer to terms relating to process analysis, students may have a better understanding of how design, equipment, and operating heuristics can be utilized in process analysis and design. Thus the MDS results may indicate that students have some understanding of how to use the heuristics, but probably do not yet fully understand where the heuristics come from and their limitations.

Two terms, HAZOP analysis and risk analysis, should have been plotted closely together but were not in the pretest or posttest. In the posttest the term HAZOP analysis moves into Cluster 3 but is still not located near risk analysis. These results suggest that students do not yet have sufficient understanding of risk in the design and operation of hazardous chemical processes, so this topic will be emphasized more thoroughly in future offerings of the process design course.

Both pretest and posttest results also suggest that the term "life-cycle analysis" may be unclear in the students' minds. Although an important concept in terms of analyzing a chemical product from "cradle to grave," the design course does not devote much time to the life cycle of chemical species, and not surprisingly, the design students have little familiarity with the concept.

The term troubleshooting remains unclustered with any other terms in both the pretest and the posttest. Although several weeks of class time were devoted to completing process troubleshooting case studies, this result may indicate that students do not understand how this concept relates to process design and analysis.

Educational implications

In this study we have used MDS as a classroom assessment technique (Angelo & Cross, 1993), a way of quickly gathering information about student progress which then can be used as a feedback mechanism to alter instruction and improve student understanding. We hope that further development of the on-line MDS web page would make it easier for instructors to use MDS as an assessment tool in their courses.

The results of the MDS cluster analysis have been used to help indicate where students have accurate knowledge of engineering design (for example, when discussing the economic analysis of a design project) and where their knowledge may be incomplete (for example, when discussing life-cycle analysis, risk analysis, and troubleshooting). This information has been used to guide the development and implementation of a new module on risk assessment and HAZOP analysis in the process design course.

Based on the results of this study, we also believe MDS can be utilized as a method for identifying misconceptions that students bring to the course (i.e. that different types of heuristics should be lumped into the same conceptual cluster instead of considering different types of heuristics as distinct tools for use on different design tasks). This information is now being used by the design course instructors to make more explicit the similarities, differences, and limitations of the types of design heuristics used in the course. New exercises have been developed to help students discover the origin and use of each type of heuristic.

We plan to use the MDS tool in future offerings of the design course to monitor the impact of the course changes mentioned above on student understanding of chemical engineering design strategies and techniques.

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